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Atomic spin gyroscope based on ^{129}Xe-Cs comagnetometer

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Atomic spin gyroscope (ASG) based on comagnetometer is a high sensitive and compact gyroscope for future inertial navigation applications. The start-up time was several hours of the demonstrated ASGs based on ^{3}He-K or ^{21}Ne-Rb-K comagnetometer, and only a few inertial navigation applications allow such a long time for preparation. We report the demonstration of an ASG based on ^{129}Xe-Cs comagnetometer, which decreases the start-up time to 10 minutes and decreases the operation temperature by 40% as well. By operating this ASG in spin exchange relaxation free regime, a sensitivity of 7×10^{-5} °/(s Hz$^{1/2}$) was achieved.

atomic spin gyroscope, comagnetometer, spin exchange relaxation free, inertial navigation

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Gyroscopes are one of the key sensors for inertial navigation applications [1], but the precision improvements of the available mechanical and optical gyroscopes have been slowly in the past decade [2]. Atomic gyroscopes have been developed in recent years, which may prove to be the next generation gyroscopes for future high precision inertial navigation applications [3]. Among atomic gyroscopes, the atomic interferometer gyroscope utilize various atomic interference effects [4,5] to sense rotation, and the atomic spin gyroscope (ASG) based on comagnetometer utilize both the electron spin of alkali metal atoms and nuclear spin of noble gas atoms to sense rotation [6]. An angular random walk (ARW) of 2×10^{-3} °/h$^{1/2}$ and a bias stability of 4×10^{-2} °/h were achieved by the ASG based on ^{3}He-K comagnetometer when it was first demonstrated. Since then, an equivalent rotation resolution of 2.5×10^{-7} °/s was obtained by the ASG based on ^{3}He-K comagnetometer [7], and an equivalent rotation resolution of 1.8×10^{-7} °/s was realized by the ASG based on ^{21}Ne-Rb-K comagnetometer [8]. Theoretic analysis showed that an ARW of 7.2×10^{-8} °/h$^{1/2}$ can be achieved in a 150 cm^{3} sense volume with ^{21}Ne based comagnetometer [9,10], which indicated that ASG based on comagnetometer is a high sensitive and compact gyroscope for future inertial navigation applications [11]. However, the demonstrated ASGs above needed several hours to spin exchange optical pump the ^{3}He or ^{21}Ne, and only a few inertial navigation applications allow such a long start-up time for preparation, which will limit the application areas with ASG significantly. Therefore there is a strong need to decrease the start-up time to expand the application areas of inertial navigation with ASG. On the other hand, the density of alkali metal atoms must be increased to enable the ASG in the spin exchange relaxation free (SERF) regime. The temperature around 190°C was operated in these demonstrated ASGs for this purpose. Such a high temperature needs high power consumption, which is difficult to be maintained stable enough under severe environments because of the large temperature gradients. Therefore, to decrease the operation temperature of the ASG is very useful for inertial navigation applications.

In this work, we report the experimental demonstration of an ASG based on ^{129}Xe-Cs comagnetometer. With this configuration, the ^{129}Xe can be easily spin exchange optical pumped by Cs in 10 minutes, due to the spin exchange cross section of ^{129}Xe-Cs is much larger than that of ^{3}He-K or ^{21}Ne-Rb [12]. The temperature is operated at 110°C to enable this ASG in SERF regime, because Cs has higher saturated vapor pressure than K and Rb. The lower operation

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temperature will not only decrease the power consumption of ASG but also open up the possibility to use the paraffin coated cell to increase the sensitivity of ASG [13,14]. We calibrate this ASG by a navigation grade precision fiber gyroscope, the test data show a sensitivity of 7×10^{-5} °/(s Hz$^{1/2}$) has been achieved.

The experimental setup is shown in Figure 1. A glass cell is placed in the center of the magnetic shield barrel, which contains a droplet of Cs metal, 20 torr of ^{129}Xe, and 100 torr of N_2. The N_2 is used as both the quenching gas and buffer gas to eliminate radiation trapping and prevent wall collisions. The cell was made in our laboratory with a cubic profile, about 25 mm on each side. To minimize the depolarizing of ^{129}Xe-wall interactions, the cell has been carefully cleaned through piranha solution before the cell was filled in gas and Cs metal. The ^{129}Xe gas used in this cell has a ^{129}Xe enrichment of 90% and a chemical purity of 99.5%.

An oven is placed outside the cell, which is heated to 110°C by flowing hot air. A Cs atom number density of 2.7×10^{13} cm^{-3} is obtained at this temperature, which is enough to guarantee the Cs atoms in SERF regime. The oven was constructed using Teflon so that it cannot generate magnetic fields in the magnetic shield barrel and can still work under the high temperature. To prevent the air flow in the optical paths, three vacuum glass tubes with high quality windows on each side are placed between the oven and the cell.

To shield geomagnetic fields for the cell, a magnetic shield barrel is used, which was made of 4 lays of high permeability metal. There are 4 holes in the barrel with 35 mm diameter to give the optical paths for pump and probe beams. After degaussing, the residual magnetic fields inside the barrel are around 5–10 nT. To further decrease the strength of residual magnetic fields, three pairs of magnetic field coils in Helmholtz configuration are used to generate uniform magnetic fields along x, y, and z directions powered by three high precision function generators. During the experiment, these coils can be used to modulate the magnetic fields, minimize the magnetic fields in x and y directions, and set an appropriate magnetic field in z direction so that the electron spin of Cs and nuclear spin of ^{129}Xe can be strongly coupled.

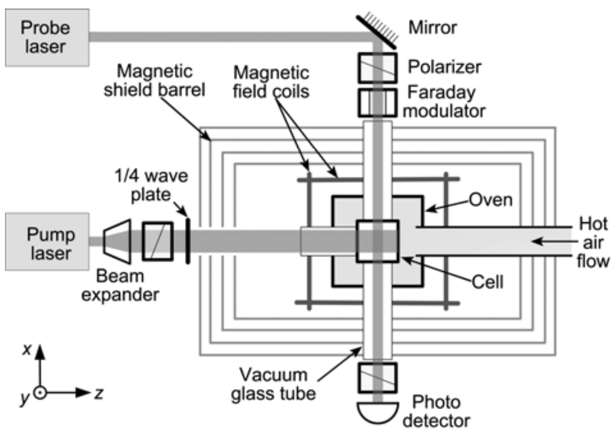

Figure 1 Schematic of the experimental setup.

A pump beam is generated by an external cavity diode laser (ECDL) at Cs D1 line, and the emitted light from this ECDL enters a tapered amplifier to have a maximum output power up to 1 W. The optical pumping of the Cs atoms is accomplished by circularly polarized laser light propagating in the z direction. A beam expander is used in the optical path to expand the pump beam to 15 mm diameter. The frequency of the pump beam is stabilized via a homemade dichroic atomic vapor laser lock (DAVLL) system. We use a cell, which contains the same components as the cell in the magnetic shield barrel, to generate a saturated absorption spectral line as the reference for DAVLL to choose the locking frequency. The exact locking point is selected at the peak of the spectral line to minimize the light shift of the pump beam.

A probe beam is generated by an ECDL with the frequency red detuned by 0.2 nm from the Cs D2 resonance. An output power of 15 mW and a beam size of 5 mm diameter are used in this experiment. Since ASG utilizes atomic spin precession to measure rotation, when a linearly polarized beam propagates through a vapor of polarized atoms, the plane of polarization of the beam will rotate an angle proportional to atomic spin along the propagation direction. Therefore a high sensitive ASG requires detection of extremely small optical rotation angles of the probe beam. We use a homemade faraday modulator to modulate the plane of polarization of the probe beam with the amplitude of 1.5° at a frequency of 6 kHz. Two Glan Taylor polarizers are placed orthogonal to each other in the optical path. A lock-in amplify receives the output from the photodetector to demodulate the signal proportional to the rotation rate. A sensitivity of 7×10^{-7} °/Hz$^{1/2}$ has been achieved with this polarimeter.

To construct the ^{129}Xe-Cs comagnetometer, a 100 nT bias magnetic field is added in z direction first. The nuclear spin of ^{129}Xe is spin exchange optical pumped for 10 minutes under this field. And then, the bias magnetic field in z direction is carefully adjusted to cancel the field created by the nuclear magnetization, so that the magnetic field which is seen by Cs atoms is nearly zero. The magnetic field in z direction is set at a value where the Larmor precession frequency (LPF) of the nuclear spin of ^{129}Xe is equal to the LPF of the electron spin of Cs. Under this condition, the nuclear spin of ^{129}Xe and the electron spin of Cs can be strongly coupled so that this comagnetometer is sensitive to rotation while the spin precession due to magnetic fields as well as their gradients and transients can be cancelled. To eliminate other signals in the output except rotation, the magnetic fields in x and y directions should be zeroed, and the pump beam and probe beam should be well aligned at 90°. These can be achieved through magnetic field modulation procedure and light power modulation procedure [9].

To test the performance of the ASG, a test apparatus is set up and shown in Figure 2. Unlike the traditional gyroscope test with rotation platform, this ASG is fixed in the optical table and the whole system is so heavy and big that traditional rotation platform cannot be used. The sense axis of this ASG is in *y* direction. To induce the rotation of ASG in this direction, the optical table is air floated first. And then, the optical table is vibrated by hand with a small angle, due to the gap between the piston and the active isolating support. A 0.03°/h fiber gyroscope with the sense axis put in *y* direction is used as a high precision rotation reference to calibrate the ASG. A date acquisition system can sample the output signals from ASG and fiber gyroscope simultaneously, and a sample frequency of 200 Hz is used in this test.

We continue to vibrate the optical table and adjust the amplitude of the vibration to get different rotation rates during the test. Response of the ASG at different rotation rates are shown in Figure 3(a), while the values of the rotation rates are given by the fiber gyroscope. We linearly fit these data and obtain a scale factor of 0.039 V/(°s) for the ASG. To compare the rotation rate of the optical table measured by the ASG and the fiber gyroscope, we change the voltage to rotation signal of the ASG with the calibrated scale factor, and plot the output of the ASG and the fiber gyroscope together in Figure 3(b). It seems that the rotation rates measured by the ASG are nearly the same as measured by the fiber gyroscope. A Fourier spectrum of the ASG rotation noise is shown in Figure 3(c), a sensitivity of 7×10^{-5} °/(s Hz$^{1/2}$) or an ARW of 4.2×10^{-3} °/h$^{1/2}$ has been achieved by this ASG. An equivalent magnetic field sensitivity of 16 fT/Hz$^{1/2}$ for this comagnetometer can be obtained as well. The peak signal at 1.4 Hz in Figure 3(c) is the horizontal resonant frequency of the optical table. Further improvement is possible by increasing active measurement volume defined by the intersection of the pump and probe beams, and decreasing the total relaxation rate by coated alkali mental cell.

In conclusion, by setting up ^{129}Xe-Cs comagnetometer and operating it in SERF regime, a sensitive ASG has been demonstrated. We reduce the start-up time of this ASG to 10 minutes, and decrease the operation temperature of this ASG to 110°C. With the start-up time decreased from hours to minutes, the application areas of inertial navigation with ASG can be expanded significantly. And with the operation temperature decreased by 40%, the power consumption of the ASG can be reduced as well. This work may open new avenues for high precision inertial navigation with ASG.

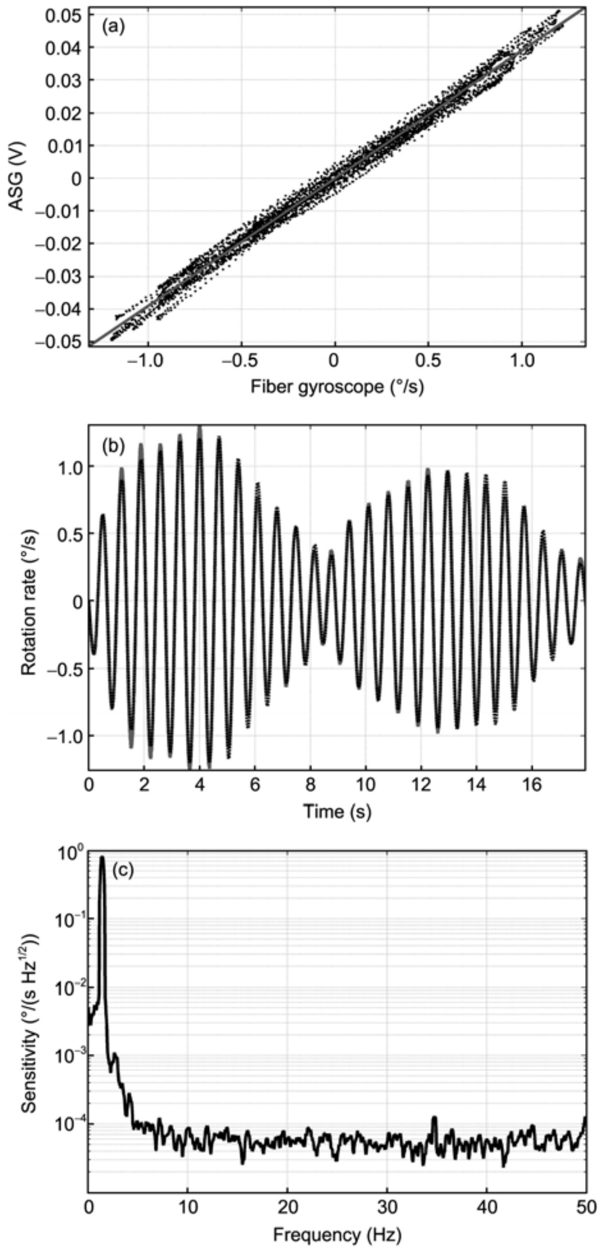

Figure 3 (a) Response of the ASG at different rotation rates which are provided by the fiber gyroscope. The solid line is a fit to calculate the scale factor of the ASG. (b) Rotation rates of the optical table measured by the ASG (solid line) and the fiber gyroscope (dashed line). (c) Fourier spectrum of the ASG rotation noise.

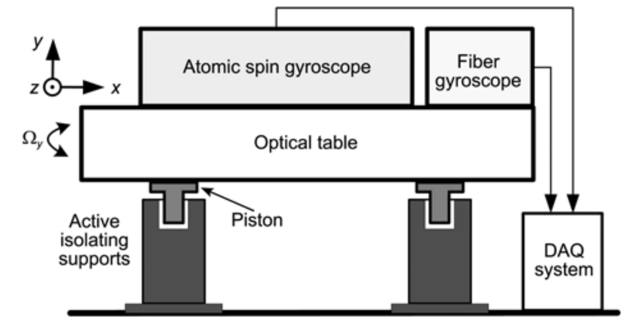

Figure 2 Schematic of the test apparatus for the ASG.

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